Overhead-Performance Tradeoffs in Distributed Wireless Networks

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14. ABSTRACT
This project studied the tradeoff between the performance of resource and link controllers in distributed wireless networks and the amount of overhead measurement and control information utilized by the controllers. The key novel idea guiding the research was to view the control signals as messages in a distributed lossy source code, and the overhead performance tradeoff as a rate distortion curve. The project began by motivating the importance of the problem by authoring a thorough review of resource control signaling in the 4G cellular standards, which observed that roughly a quarter to a third of all downlink time-frequency resources are spent on non-information bearing control information that is not efficiently encoded. Three simple resource controllers were then investigated, and their overhead performance rate distortion function was calculated using a novel adaptation of the Blahut Arimoto algorithm to the CEO problem with independent sources. Practical source compressors and quantizers for both interactive and non-interactive control scenarios were developed that approached the associated fundamental limits. Extensions to controllers for multiuser MIMO communications and joint source channel codes for the control information were also considered.

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Final Project Report:
Overhead-Performance Tradeoffs in Distributed Wireless Networks
(AFOSR FA9550-12-0086)

John MacLaren Walsh, Steven Patrick Weber,
Leonard Cimini, Javier Garcia-Frias

June 26, 2015

Contents

1 Overview

The overarching goal of this project was to characterize the tradeoff between overhead and performance for resource allocation, link adaptation, and control in distributed wireless networks. Different practical resource control, link adaptation, and scheduling algorithms, ranging from completely academic to those already specified in standards, were considered through the lens of the overhead they require to meet a given performance. The project considered performance primarily from physical layer centric metrics such as spectral efficiency.

The key novel idea guiding the research was that wireless network and resource control algorithms, which must all make decisions dependent on network state that is distributed throughout the network and not available at any one location, could be viewed as distributed lossy source codes designed for computing control functions. As reviewed in §2, distributed lossy source coding and distributed and interactive function computation theory can then characterize the tradeoff between overhead and performance through a rate distortion function, where the rate reflects the amount of overhead, and the distortion reflects the gap between the performance of the decisions made and those an omniscient controller would make.

To make a case to the community for the need for the research, the project began with a thorough analysis of the overhead required for the resource measurement and control signaling in the 3GPP LTE and LTE advanced standards, briefly reviewed in §2.1. A tutorial on this topic was written, which elucidated that the present wireless standards waste nearly a quarter to a third of downlink transmission on poorly encoded non-information bearing resource measurement and control signals. This enabled the investigators to make a strong case for studying the optimal encoding of control signals for wireless resource allocation. Previous studies along these lines have focused on adaptation of a single link, with extensive prior research studying rate distortion functions and compressors being designed for precoding matrices for MIMO communications. However, very little work has considered the design of compressors angled at computing a function that depends on the channel state of multiple users simultaneously, and it was precisely this subject that the project set out to investigate.

Next, we set out on analyzing the fundamental limit for the overhead performance tradeoff for a family of simple scheduling algorithms as described in §2.3. Three different, but closely related, schedulers reflecting three different collections of physical layer capabilities were selected. The first scheduler, motivated by an adaptive modulation and coding based physical layer, aimed to both select a user with the highest channel quality to schedule, as well as learn this users channel quality, thus computing both an arg-max and a max across users. The second scheduler, motivated by a physical layer utilizing a sophisticated hybrid-ARQ or rateless coding scheme, aimed only to learn the identity of a user with the highest channel quality, thus computing only an arg-max. The third scheduler was based on an any-cast oriented physical layer desiring to communicate a common message to any user with the highest channel quality, and thus computing only a max.

Using multiterminal information theory, the minimum amount of information to compute these three schedulers with a given performance/spectral efficiency accuracy, was determined as an instance of a rate distortion function. It was shown that, although some small rate savings relative to blindly forwarding channel state are possible when computing the functions losslessly in a non-interactive manner, substantial rate savings scaling favorably in the number of users can be obtained if either interaction between the controller and users is allowed, or some loss can be tolerated by the scheduling algorithm, or both. In order to compute the associated rate distortion tradeoffs, a new variant of the Blahut Arimoto algorithm was designed for lossy distributed function computation as reviewed in §2.2. Additionally, practical source compressors and quantizers reviewed in §2.3 and §2.4 were designed which approached the rate distortion limits for both non-interactive and interactive cases, resp., of the three simple scheduling models above as well as for more complicated link adaptation models from relay selection (§3.2) and multiple user MIMO communications (§3.1). Also, motivated by the need not-only to compute control decisions at a controller in a manner requiring minimal information exchange with users in the network, but also to convey the salient part of the control decisions back to the users over their unreliable and unknown channels, the project exerted substantial effort on the joint source channel rateless coding problem as described in §4.

In summary, the research on the project thoroughly demonstrated the importance of the focus on the design of encodings of control signals in wireless systems, and that these designs can be guided by fundamental limits set out by multiterminal source coding theory and recipes from practical quantizers for function computation.

2

2 Viewing Resource Controllers as Lossy Source Codes

A key characteristic of resource allocation and link adaptation in distributed wireless networks is that the performance of a certain collection of resource allocation and link adaptation control decisions is dependent on channel and queue state information that is distributed throughout the network. A naive method of implementing such a controller, whose ideal performance upper bounds that of any other resource allocation and link adaptation algorithm, is to collect all of this network state at single controller in the network, which then makes allocation and adaptation decisions which are forwarded back to the network participants. If this controller is perfectly omniscient, and its knowledge of network state is current and flawless, then the controller achieves the best performing resource allocation and link adaptation decisions possible.

However, a large part of what is interesting about resource allocation and link adaptation is that the entire wireless network state is not available at any one location in the network. In a centralized control architecture, the information regarding channel and queue measurement, and then the subsequent decisions made from it, must share the same unreliable wireless resources as the data and additionally must be robust against a wide variety of channel conditions, forming in aggregate overhead control and measurement information. Intuitively, one would expect a tradeoff between the overhead an optimized distributed wireless network controller collects and the performance on the data-bearing signals it achieves: the more information about the network state is available, the better the performance of the resource decisions on the data-bearing portion of the signaling.

A major goal of this project was to study this tradeoff between overhead and performance as a rate distortion curve by viewing a network resource allocation and link adaptation algorithm as a distributed lossy source code. The various network states, channel qualities and queue characteristics, were viewed as observations at a series of source encoders, and the decisions made by the central wireless resource controller were viewed as the output of a central decoder. Each of the source encoders sent a rate limited message to the central decoder, with the rate of the messages representing the overhead of the control and measurement scheme. In this way, the design of control and measurement signaling algorithms was viewed as an instance of the CEO problem in lossy distributed source coding theory (see §2.2 and Fig. 2). The distortion or loss was quantified by the loss in performance relative to the performance an omniscient centralized controller could achieve.

Calculating the sum-rate distortion curve for this CEO problem then yielded the fundamental limit over all control and measurement signal encoding schemes for the tradeoff between overhead and performance. Several issues then arose. To begin with, it was of interest to characterize the overhead and performance obtained by practical wireless resource controllers that are already deployed, as described in §2.1, as well as several that remain substantially more theoretical as described in §3. Next, it was of interest to obtain the fundamental rate distortion limits for overhead performance tradeoffs for a series of simple resource allocation control algorithms as described in §2.3.

With the fundamental limits in hand, the next issue was to design practical control and measurement signaling schemes to approach them. Here, as described in §2.3, we used several variants on simple scalar quantization, and discovered that, for the models and distortion metrics in this problem, certain classes of scalar quantizers can yield performance close to the rate distortion limit.

However, these models did not allow for interaction between the centralized controller and the users over multiple rounds of feedback before making control decisions. Our research showed that, if such interaction is allowed, then the aggregate amount of rate to meet a necessary performance can be substantially lower. However, the delay incurred with multiple rounds of round-trip interactive communication can make control decisions stale. In this scenario, even if perfect omniscient resource decisions are to be calculated, the tradeoff between the overhead rate and the delay at which these decisions can be calculated is of interest. For this reason, interactive scalar quantization schemes were investigated as described in §2.4, and their optimized tradeoff between rate and delay were calculated.

The initial optimized interactive scalar quantization schemes involved solving dynamic programs which could become computationally infeasible as the size of the problem grew. For this reason, we considered suboptimal dynamic programs of substantially lower complexity which we were able to both demonstrate and prove yielded performance very close to the optimal dynamic program, see §2.4 Fig. 6.

2.1 Motivation from 4G Cellular Standards

To provide motivation for the important of studying how to efficiently encode control signals for modern wireless systems, an early focus in the project was reviewing the 4G wireless standards, studying both the way control and measurement signals are encoded, as well as their time-frequency footprint. The results from this study were written in a tutorial article on the topic of resource allocation and link adaptation in LTE and LTE advanced. A key realization from this study was that, as shown in Fig. 1, nearly a third of all time frequency resources in LTE are spent on non-information bearing control and reference signals.
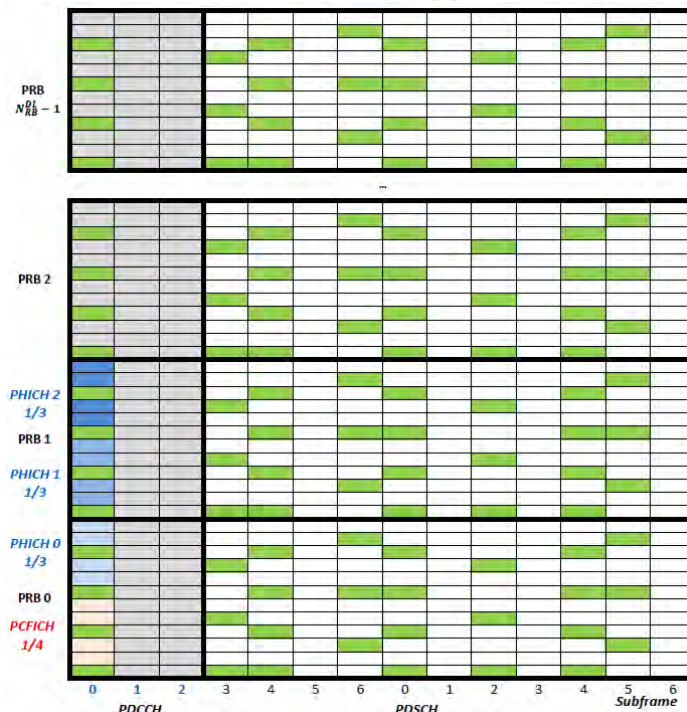
Figure 1: The time frequency resource plane for the downlink in the LTE standard. The grey region represents control information while the green regions reflects reference signals. The control signals occupy roughly a quarter of downlink transmission, and with the reference and measurement signals, the non-information bearing overhead in the downlink stands at about a third. LTE advanced required extra control and reference signals which further grew this fraction. See the tutorial for details and acronym definitions.

Key Publication & Abstract

- Gwanmo Ku and John MacLaren Walsh, Resource Allocation and Link Adaptation in LTE & LTE Advanced: A Tutorial, *IEEE Communications Surveys and Tutorials*, to appear. 29 double column pages. [Online]. Available: `http://dx.doi.org/10.1109/COMST.2014.2383691`

  - Resource allocation and link adaptation in long term evolution (LTE) and LTE Advanced are discussed with a focus on the location and formatting of the pertinent reference and control signals, as well as the decisions they enable. In particular, after reviewing the units for resource allocation and the time frequency resource grid, the enabled resource allocation modes and their purposes are reviewed. A detailed description of the way the resource allocations are encoded under these different modes is also given. Similarly, the various methods of link adaptation, including power control and rate control, both through the use of adaptive modulation and coding and hybrid ARQ, are reviewed. The control signaling encoding for link adaptation is provided in detail, as is the encoding of channel state feedback for the purposes of link adaptation and resource allocation.

4

2.2 Blahut Arimoto Algorithm for CEO Problem with Independent Sources

The project then set out to determine the fundamental limits for the tradeoff between overhead and performance as set out by multiterminal information theory by modeling the resource control signaling problem as the CEO problem, depicted in Fig. 2, left. Although the general CEO problem's rate distortion region is unknown, it was pointed out that when the sources are independent, an expression for the rate region can be obtained. This rate distortion region, when applied to an appropriate source distribution and distortion for a resource control model, gives the tradeoff between the rates sent by users and the performance loss obtained by the controller. A new algorithm, Fig. 2, right, was devised for computing this rate distortion region and the sum rate distortion function by generalizing the Blahut Arimoto algorithm. This algorithm was then applied to models for resource control problem to obtain fundamental limits for the tradeoff between feedback information and the performance of the controller, as described in §2.3, after which practical quantization schemes approaching these limits were devised.
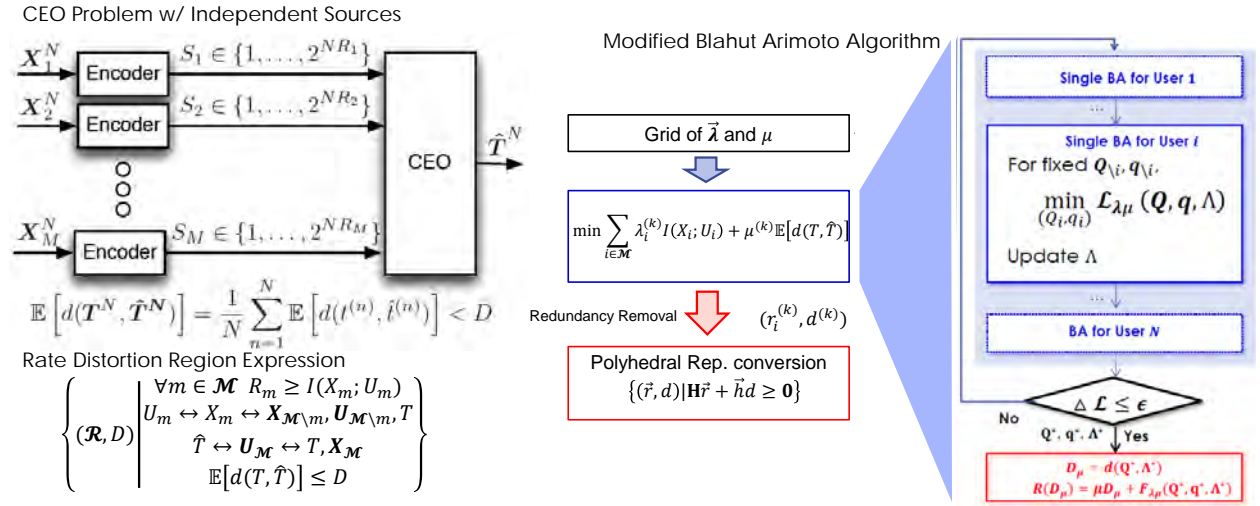

Figure 2: Left: the CEO problem with independent sources and its rate distortion region expression. Right: The algorithm devised under the project to compute this rate region expression for particular models. This algorithm was applied to compute fundamental limits for overhead performance tradeoffs.

Key Publication & Abstract

- Gwanmo Ku, Jie Ren, and John MacLaren Walsh, Computing the Rate Distortion Region for the CEO Problem with Independent Sources, *IEEE Trans. Signal Processing*, vol. 63, no. 3, pp. 567–575, Mar. 2015. [Online]. Available: http://dx.doi.org/10.1109/TSP.2014.2379631

  – A method for numerically calculating the rate distortion region for the central estimation officer (CEO) problem when the sources are independent is derived by generalizing the Blahut-Arimoto algorithm. Unlike the traditional rate distortion function computation problem, the Lagrangian for the CEO rate distortion region can be non-convex. When the Lagrangian is convex, the presented algorithm is converges from every initialization to the global optimum under some additional uniqueness conditions. When the Lagrangian is non-convex, the convergent value obtained by the algorithm can be initialization dependent. To handle these non-convex cases, an explicit non-random initialization that is in the region of attraction of the global optimum for low distortions is provided. Some example problems motivated by remote lossy function computation in sensor networks and wireless resource controllers highlight that both the convex and non-convex cases occur in practice, and the utility of the algorithm in computing their rate distortion regions.

2.3 Fundamental Tradeoffs & Practical Quantizers for Three Resource Controllers

Having assembled the tools to calculate rate distortion functions and regions for the types of lossy distributed function computation problems that model distributed wireless resource controllers, the project's next goal was to calculate fundamental limits for overhead performance tradeoffs for some simple resource control problems.

Three different, but closely related, schedulers reflecting three different collections of physical layer capabilities were selected for the situation in OFDMA based resource allocation and link adaptation depicted in Fig. 3, left. The first scheduler, motivated by an adaptive modulation and coding based physical layer, aimed to both select a user with the highest channel quality on each subband to schedule, as well as learn this users channel quality, thus computing both an arg-max and a max across users. The second scheduler, motivated by a physical layer utilizing a sophisticated hybrid-ARQ or rateless coding scheme, aimed only to learn the identity of a user with the highest channel quality, thus computing only an arg-max. The third scheduler was based on an any-cast oriented physical layer desiring to communicate a common message to any user with the highest channel quality, and thus computing only a max.

The modified Blahut Arimoto algorithm from the previous section was then used to calculate the sum-rate distortion function for computing these three functions at the base station from rate limited channel state messages from the users. It was shown that, although some small rate savings relative to blindly forwarding channel state are possible when computing the functions losslessly in a non-interactive manner, substantial rate savings scaling favorably in the number of users can be obtained if either interaction between the controller and users is allowed, or some loss can be tolerated by the scheduling algorithm, or both. The fundamental overhead performance tradeoffs for these three functions calculated with the algorithm in the previous section for for two users and the 16 channel qualities in the LTE standard are depicted at the right of Fig. 3.
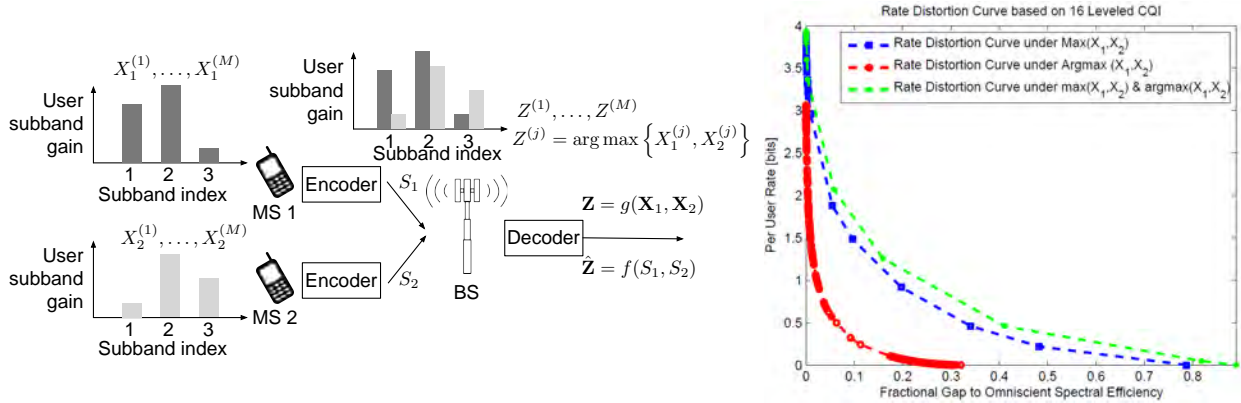

Figure 3: Left: The simple resource controllers investigated were designed to allocate sub-bands to those users with the best channel quality on the sub-bands. Three cases were considered based on three different physical layer architectures: computing a user with the maximum sub-band gain on each sub-band ($\arg\max$), computing a user with the maximum sub-band gain and its gain ($\max, \arg\max$), and simply computing the maximum sub-band gain across users ($\max$). Right: Sample overhead performance tradeoffs for these 3 functions calculated with the algorithm from previous section.

Having established the fundamental limits for the control signaling schemes for these three controllers, the subject shifted to designing practical channel state quantization schemes which could approach these limits. We began by devising a quantization scheme that would be the same for each user – homogeneous scalar quantization, and then comparing it with a scheme which allowed different users to use different quantizers – heterogeneous scalar quantization. Fig. 4 depicts the performance of both of these schemes, and it was shown that, while using heterogeneity provided a benefit, this benefit was small and diminished as the number of users grew. The designed homogenous scalar quantizers yielded performance close to the fundamental limits that had been previously obtained.
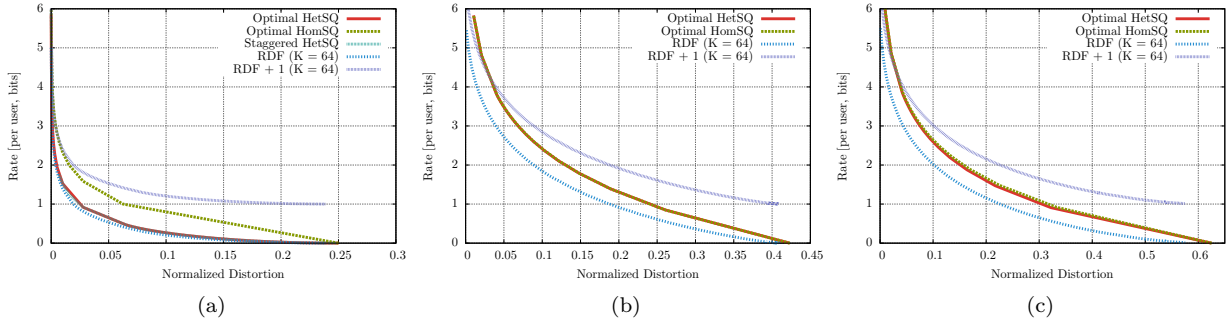
Figure 4: Rate distortion tradeoff for numerically optimized heterogenous scalar quantization for two users with sources distributed Uniform$(0, 1)$: (a) arg max; (b) max, and; (b) (arg max, max). The rate-distortion performance of homogeneous scalar quantization and heterogeneous scalar quantization is compared to the rate-distortion function. For the purposes of comparison, we have included a trendline for the rate distortion function plus a bit.

Key Publications & Abstracts

- B. D. Boyle, J. M. Walsh, and S. Weber, Distributed scalar quantizers for subband allocation, in *Proc. of Conf. Information Sciences and Systems (CISS)*, March 2014.

  – Efficient downlink resource allocation (e.g., subbands in OFDMA/LTE) requires channel state information (e.g., subband gains) local to each user be transmitted to the base station (BS). Lossy encoding of the relevant state may result in suboptimal resource allocations by the BS, the performance cost of which may be captured by a suitable distortion measure. This problem is an indirect distributed lossy source coding problem with the function to be computed representing the optimal resource allocation, and the distortion measuring the cost of suboptimal allocations. In this paper we investigate the use of distributed scalar quantization for lossy encoding of state, where the BS wishes to compute the index of the user with the largest gain on each subband. We prove the superiority of a heterogeneous (across users) quantizer design over the optimal homogeneous quantizer design, even though the source variables are IID.

- Jie Ren, Bradford Boyle, Gwanmo Ku, Steven Weber, John MacLaren Walsh, Overhead Performance Tradeoffs A Resource Allocation Perspective, *IEEE Trans. Inform. Theory*, submitted on August 14, 2014. 70 single column pages. [Online]. Available: `http://arxiv.org/abs/1408.3661`

  – A key aspect of many resource allocation problems is the need for the resource controller to compute a function, such as the max or arg max, of the competing users metrics. Information must be exchanged between the competing users and the resource controller in order for this function to be computed. In many practical resource controllers the competing users' metrics are communicated to the resource controller, which then computes the desired extremization function. However, in this paper it is shown that information rate savings can be obtained by recognizing that controller only needs to determine the result of this extremization function. If the extremization function is to be computed losslessly, the rate savings are shown in most cases to be at most 2 bits independent of the number of competing users. Motivated by the small savings in the lossless case, simple achievable schemes for both the lossy and interactive variants of this problem are considered. It is shown that both of these approaches have the potential to realize large rate savings, especially in the case where the number of competing users is large. For the lossy variant, it is shown that the proposed simple achievable schemes are in fact close to the fundamental limit given by the rate distortion function.

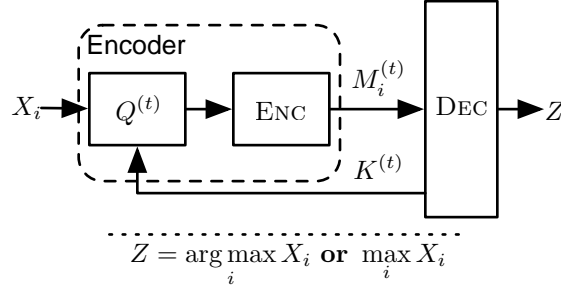## 2.4 Interactive Quantization and Rate Delay Tradeoffs

Figure 5: Interactive quantization in the CEO problem.

In the system model in the previous section, the resource controller could incur some loss in computing its control function, but the users were not allowed to interact with the base-station: the function needed to be learned from a single series of messages sent by the users without any feedback or information sent from the basestation.

The ability to interact was shown to greatly change the fundamental limits for losslessly computing the function, with gigantic savings in the interactive case relative to the simple situation in which all of the channel states were simply forwarded. This motivated the study of quantization schemes in which the users were allowed to interact with the base-station over several rounds. Since each round of interaction must represent a substantial delay in a real wireless system, our computations for this work focussed on the tradeoff between the expected exchanged rate and the expected number of rounds required to compute the function.

The model selected for this problem is depicted in Fig. 5. At each round in the interaction each user is either awake or asleep, and once a user is asleep they remain so. At each round, all users which are awake use the same quantizer to send the CEO a quantized representation of their source. The basestation stops when it has computed its desired function, either max or arg max in this case.

The best quantization scheme for this setup was computed using dynamic programming, yielding the rate delay trade-offs depicted in Fig. 7. Because the complexity of this dynamic program can grow high as the number of users and the size of the random variable supports grow, several suboptimal solutions to the dynamic program that had low complexity were developed. It was shown, as in Fig. 6, that they yielded performance close to that of the optimal solutions.
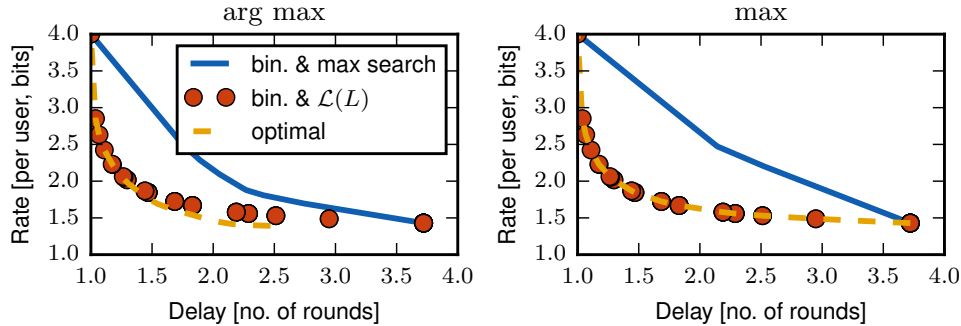

Figure 6: Comparison of rate-delay trade-off for various quantizer search spaces when computing $\arg\max$ (left) and max (right). The source distribution was uniform with support set size $L = 16$ and the number of users was $N = 4$.
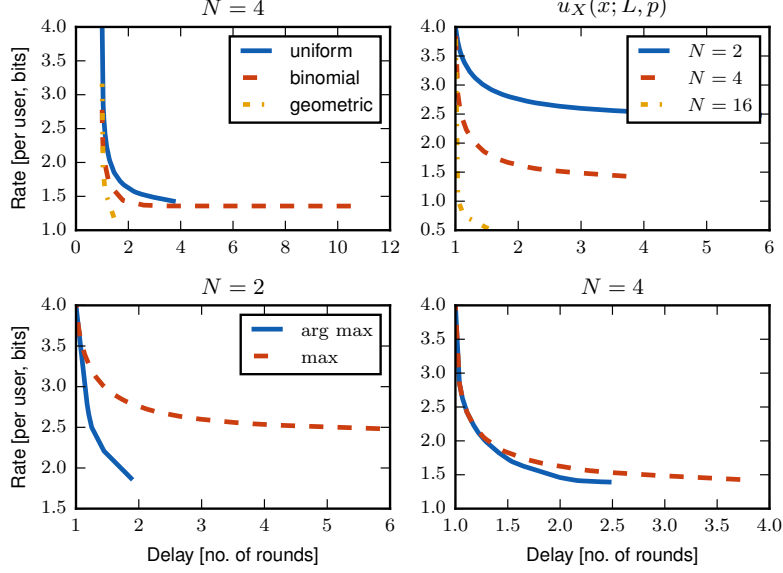
Figure 7: Comparison of rate-delay trade-offs: *(top, left)* for uniform, $g_X(x; L, p)$, and $b_X(x; L, p)$ ($L = 16$), *(top, right)* when computing the max for varying number of users (N), and *(bottom)* when computing arg max vs. max for $N = 2$ (right) and $N = 4$. The source distribution was uniform with support set size $L = 16$.

Key Publications & Abstracts

- J. Ren and J. M. Walsh, Interactive communication for resource allocation, in *Proc. of Conf. Information Sciences and Systems (CISS)*, March 2014.

  - For the resource allocation problem in a multiuser OFDMA system, we propose an interactive communication scheme between the base station and the users with the assumption that this system utilizes a rateless code for data transmission. We describe the problem of minimizing the overhead measured in the number of bits that must be exchanged required by the interactive scheme, and solve it with dynamic programming. We present simulation results showing the reduction of overhead information enabled by the interactive scheme relative to a straightforward one-way scheme in which each user reports its own channel quality.

- Bradford D. Boyle, Jie Ren, John MacLaren Walsh, and Steven Weber, Interactive Scalar Quantization for Distributed Extremization, *IEEE Trans. Signal Processing*, submitted on May 15, 2015. 28 single column pages. [Online]. Available: http://arxiv.org/abs/1505.04202

  - In many resource allocation problems, a centralized controller needs to award some resource to a user selected from a collection of distributed users with the goal of maximizing the utility the user would receive from the resource. This can be modeled as the controller computing an extremization of the distributed users' utilities. The overhead rate necessary to enable the controller to reproduce the users' local state can be prohibitively high. Two approaches to reduce this overhead are lossy estimation and interactive communication. In the lossy estimator framework, rate savings are achieved by tolerating a bounded expected reduction in utility. In interactive communication, rate savings come at the expense of delay. In this paper, we consider the design of a simple achievable scheme based on successive refinements of scalar quantization at each user. The optimal quantization policy is computed via a dynamic program and we demonstrate that tolerating a small increase in delay can yield significant rate savings. We then consider two simpler quantization policies to investigate the scaling properties of the rate-delay trade-offs. Using a combination of these simpler policies, the performance of the optimal policy can be closely approximated with lower computational costs.

3 Overhead Performance Tradeoffs in MIMO Cooperative Communications & Relaying

The models for resource allocation in the previous sections were somewhat simple. The research effort in these sections aimed to look at the tradeoff between overhead and performance in more sophisticated models involving multiple user MIMO communications and cooperative relaying.

3.1 Limited Feedback Quantization for Multi-user MIMO

This work considered several MIMO channel state feedback quantization schemes for the multi-user MIMO broadcast channel as depicted in Fig. 8. A quantization scheme, sparse coded quantization was shown to have performance between scalar quantization and vector quantization which reduced complexity relative to vector quantization.
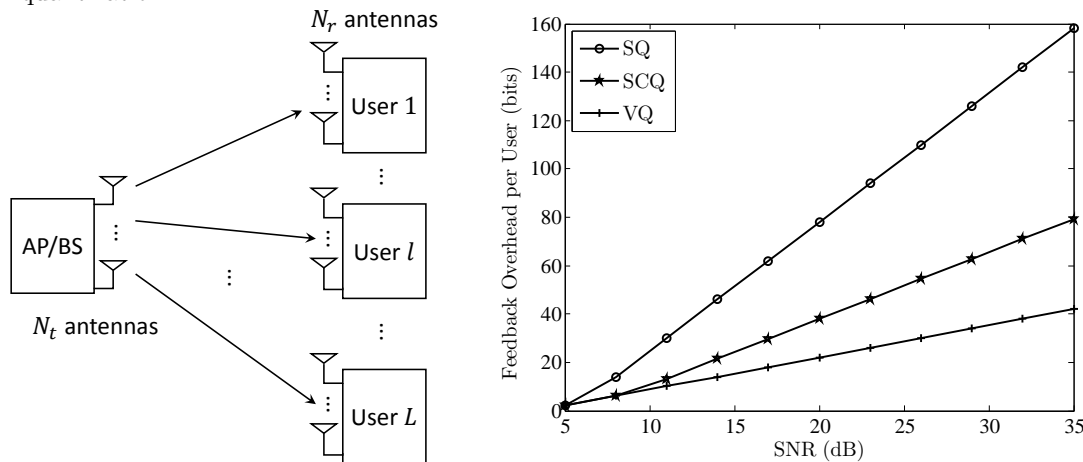

Figure 8: Left: The multi-user MIMO broadcast channel with L users. The AP/BS is equipped with N_t antennas and each user has N_r antennas. We assume $N_t = LN_r$. Right: the overhead required by several quantization schemes for channel state feedback for MU-MIMO in this problem.

Key Publications & Abstracts

- Q. Wang, H. Feng, L. J. Cimini, L. J. Greenstein, D. S. Chan, and A. Hedayat, Sparse coding quantization for downlink MU-MIMO with limited CSI feedback, in Proc. of IEEE MILCOM, Nov. 2013.

  - A novel quantization method, sparse coding quantization (SCQ), is proposed for downlink multiuser multiple-input multiple-output (MU-MIMO) systems. Compared to conventional vector quantization (VQ), SCQ utilizes a linear combination of several codewords rather than a single one to represent the channel matrix. Both analytical and simulation results reveal that the proposed technique can achieve the same sum rate performance as VQ at a reasonable cost in feedback overhead. Thus, SCQ is more practical because it significantly reduces the time and space complexity for generating, searching and storing the codebook.

- Q. Wang, H. Feng, L. J. Cimini, L. J. Greenstein, D. S. Chan, and A. Hedayat, Comparison of quantization techniques for downlink multi-user MIMO channels with limited feedback, IEEE Wireless Commun. Lett., vol. 3, no. 2, pp. 165-168.

  - This letter evaluates three quantization techniques for downlink multiple-user multiple-input multiple-output (MU-MIMO) systems with limited feedback. The required feedback bits for a specified rate loss are quantified, as well as the complexity for each technique. Furthermore, the net capacity, which incorporates the effect of the overhead, is studied. The analysis and simulation results reveal the advantages and drawbacks of each quantization method and demonstrate under what conditions to use one of them rather than the other.

3.2 Impact of Overhead on Spectral/Energy Efficiency of Cooperative Relaying

The wireless infrastructure models in the previous sections focussed on cellular or access-point oriented models, while the research project also aimed to understand infrastructures inspired by cooperative communications in mobile ad hoc networks. For this reason, the problem of users selection in cooperative relaying, as depicted in Fig. 9, left, was selected. The overhead performance tradeoffs of several schemes were calculated and compared as depicted in Fig. 9, right.
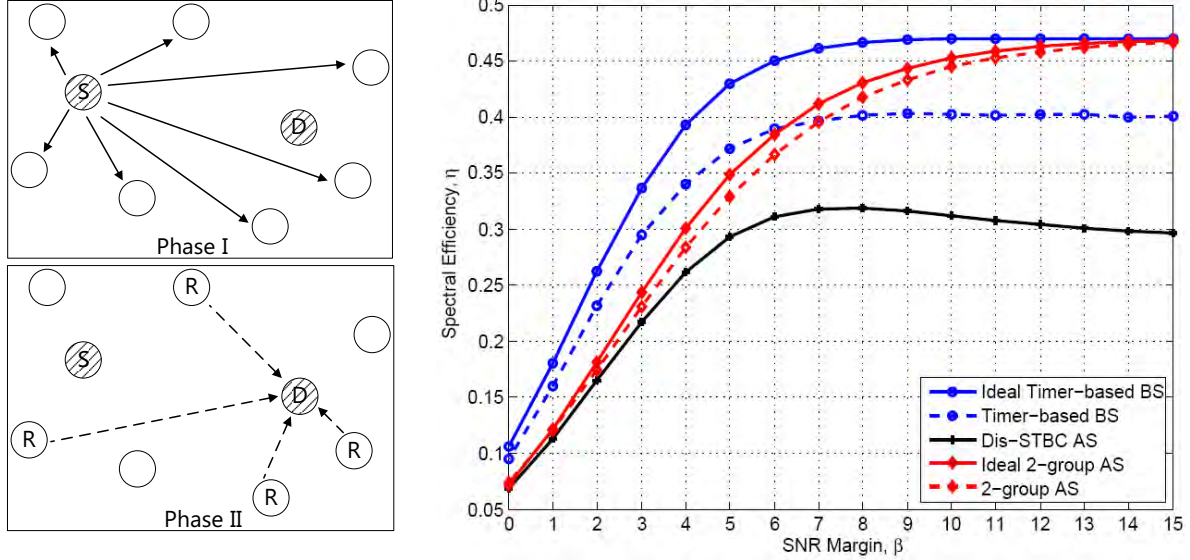

Figure 9: Several schemes for achieving cooperative relaying and their overhead performance tradeoffs.

Key Publications & Abstracts

- Y. Xiao and L. Cimini, Impact of overhead on spectral efficiency of cooperative relaying, *IEEE Trans. Wireless Commun.*, May 2013. (DOI: 10.1109/TWC.2013.120779).

  - It is well known that cooperative relaying has the potential to improve the performance of wireless communication. However, compared with point-to-point communication, cooperative relaying requires much more overhead to implement. In this paper, we quantitatively analyze the overhead in implementing cooperative relaying, in particular, the overhead to acquire essential channel state information, to select the relay(s), and to provide the required coordination. Factoring in the impact of overhead, the spectral efficiency of cooperative relaying schemes is then investigated. A comparison of three cooperative relaying schemes (Timer-Based Best-Select, Distributed Space-Time-Coded, and M-group) is presented. Numerical results are provided to illustrate the impact of overhead on the spectral efficiency. Finally, based on the analysis and simulations, we provide guidelines for determining the appropriate cooperative relaying scheme for specific scenarios.

- Y. Xiao and L. Cimini, Spectral efficiency of cooperative relaying with imperfect channel estimation, in Proc. IEEE Int. Conf. on Commun. (ICC), June 2012.

  - It is well known that cooperative relaying has the potential to improve the performance of end-to-end wireless communications. However, compared to point-to-point communications, implementing cooperative relaying requires much more overhead. For example, more complicated coordination and transmission schemes are required. In this paper, the spectral efficiency of cooperative relaying is investigated, taking into account the overhead to acquire essential channel state information, as well as that required to select the relay(s). A comparison of three cooperative relaying schemes (Timer-based Best-Select relaying, Dis-STBC All-Select relaying, and M-group All-Select relaying) is presented. Numerical results are further provided to illustrate the impact of the overhead on the spectral efficiency.

4 Design of Rateless Joint Source Channel Codes

We have studied novel rateless coding schemes for high throughput transmission for a wide range of single and multi-terminal sources and different channel environments. Different from existing rateless systems, we have focused on the application of hybrid analog-digital joint source-channel coding schemes, inspired in novel developments in the field of analog joint source-channel coding.

The hybrid schemes we have developed consist of two sub-blocks concatenated in parallel: on the one hand, a digital channel encoder, which produces coded bits from the input bits, as in standard rateless systems. On other hand, a digital-to-analog encoder, which produces real numbers (or multiple discrete points) from the input bits. The idea of this research is to take advantage of the analog component of the hybrid scheme to obtain high throughput communications, and more robustness against changes in the channel conditions, something that would be difficult to achieve if only standard digital channel codes were utilized. On the other hand, the use of pure digital-to-analog encoders would lead to significant error floors, with the consequent performance degradation. Thanks to the use of the digital channel code sub-block, these error floors can be substantially reduced to achieve excellent performance.

Key Publications & Abstracts:

- L. Li and J. Garcia-Frias, "Hybrid Analog-Digital Coding Scheme Based on Parallel Concatenation of Linear Random Projections and LDGM Codes", CISS'14, Princeton, NJ, March 2014.

    - This paper aims at designing a hybrid analog digital coding scheme that can be applied for rate adaption in a broad dynamic range of channel conditions. The hybrid scheme is constructed by generating most of the output symbols from standard linear combinations of the input bits, as in Rate Compatible Modulation (RCM), and a few of them using a Low Density Generator Matrix (LDGM) code. RCM is able to achieve smooth rate adaption, but its performance is far from the Shannon theoretical limits. The few coded bits proceeding from the LDGM code are able to substantially reduce the number of uncorrected errors in the RCM scheme, substantially improving the system performance.

- L. Li and J. Garcia-Frias, "Hybrid Analog-Digital Coding for Nonuniform Memoryless Sources", CISS'15, Baltimore, MD, March 2015.

    - We propose a hybrid analog-digital scheme for the transmission of non-uniform memoryless sources over Additive White Gaussian Noise (AWGN) channels. The hybrid scheme is constructed by generating most of the output symbols from standard linear combinations of the input bits, as in Rate Compatible Modulation (RCM), and a few of them using a Low Density Generator Matrix (LDGM) code. The basic idea is that the RCM scheme corrects most of errors, leaving residual errors to be corrected by the LDGM code. Source non-uniformity is exploited at the decoder and the encoder is optimized depending on the source non-uniformity to further improve the system performance.

- O. Fresnedo, J. P. Gonzlez-Coma, M. Hassanin, L. Castedo, and J. Garcia-Frias, "Evaluation of Analog Joint Source-Channel Coding Systems for Multiple Access Channels", To appear in *IEEE Transactions on Communications*.

    - We address the evaluation of low-complexity analog Joint Source Channel Coding (JSCC) methods for the transmission of discrete-time analog symbols over Multiple-Input, Multiple-Output (MIMO) Multiple Access Channels (MAC). Analog JSCC is employed to encode the source information at each transmitter prior to be directly input to the MAC access scheme. Three channel access methods are considered to ensure the receiver is able to recover the user information: Code Division Multiple Access (CDMA), linear MMSE access codes and opportunistic access. CDMA allows the orthogonal transmission of the user data requiring only Channel State Information (CSI) at reception. On the other hand, linear MMSE access codes exploit CSI knowledge at transmission and exhibit better performance. Finally, opportunistic access also exploits CSI at transmission and allocates all MAC resources to the user with the strongest channel. This latter access scheme exhibits the best performance in terms of sum distortion although it may lead to unfair rate distributions among users.

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5 Abstracts of Doctoral Dissertations

- Gwanmo Ku, *Efficient Control Signaling for Resource Allocation in OFDMA Networks*, Ph.D. dissertation, Drexel University, 2014. [Online]. Available: `http://www.ece.drexel.edu/walsh/Ku_PhD.pdf`

  - This thesis designs efficient control signaling for resource allocation in OFDMA networks, with special attention given to improving the resource controller in the LTE standard. We are interested in two aspects of resource controller design, the amount of control information a resource controller utilizes, and the performance, for instance the data spectral efficiency, it attains. Our overall aim is to understand the fundamental tradeoff between these two quantities, and to learn how to design resource controllers that approach this tradeoff.

    To get a sense of the state of the art in resource controller design, we first investigate the resource controller in the LTE standard, evaluating the amount of control information it requires. We thoroughly catalog the physical layer signals related to resource allocation and link adaptation with a focus on the location and formatting of the pertinent reference and control signals, as well as the decisions they enable. This enables us to determine the fraction of the time frequency resource grid spent on control information. This control signaling overhead in LTE occupies a large percentage of the time-frequency footprint of wireless network traffic and is not efficiently encoded.

    After this, we set about determining the fundamental tradeoff between the amount of control information and the spectral efficiency by modeling the problem using information theory. In order to design more efficient control signaling schemes, we will model the control signals as messages in a distributed lossy source code, for which the rate distortion function describes an optimum tradeoff between a rate, reflecting the overhead, and a distortion, reflecting the performance. Although there is no closed form expression for the rate region, we derive a novel adaptation of the Blahut-Arimoto algorithm to the CEO model with independent sources, and use it to numerically calculate the rate distortion function. The developed algorithm is then utilized to calculate the rate distortion function for a series of simple resource allocation models.

    Finally, for these physical layer resource allocation models, we design practical distributed quantizers that yield control signaling encodings for a resource controller that approaches the fundamental overhead performance tradeoff limit calculated.

- Bradford Boyle, *Achievable Schemes for Cost/Performance Trade-offs in Networks*, Ph.D. dissertation, Drexel University, 2015.

  - A common pattern in communication networks (both wired and wireless) is the collection of distributed state information from various network elements. This network state is needed for both analytics and operator policy and its collection consumes network resources, both to measure the relevant state and to transmit the measurements back to the data sink. The design of simple achievable schemes are considered with the goal of minimizing the overhead from data collection and/or trading off performance for overhead. Where possible, these schemes are compared with the optimal trade-off curve.

    The optimal transmission of distributed correlated discrete memoryless sources across a network with capacity constraints is considered first. Previously unreported properties of jointly optimal compression rates and transmission schemes are established. Additionally, an explicit relationship between the conditional independence relationships of the distributed sources and the number of vertices for the Slepian-Wolf rate region is given.

    Motivated by recent work applying rate-distortion theory to computing the optimal performance-overhead trade-off, the use of distributed scalar quantization is investigated for lossy encoding of state, where a central estimation officer (CEO) wishes to compute an extremization function of a collection of sources. The superiority of a simple heterogeneous (across users) quantizer design over the optimal homogeneous quantizer design is proven.

    Interactive communication enables an alternative framework where communicating parties can send messages back-and-forth over multiple rounds. This back-and-forth messaging can reduce the rate required to compute an extremum/extrema of the sources at the cost of increased delay.

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Again scalar quantization followed by entropy encoding is considered as an achievable scheme for a collection of distributed users talking to a CEO in the context of interactive communication. The design of optimal quantizers is formulated as the solution of a minimum cost dynamic program. It is established that, asymptotically, the costs for the CEO to compute the different extremization functions are equal. The existence of a simpler search space, which is asymptotically sufficient for minimizing the cost of computing the selected extremization functions, is proven.

- Hao Feng, *Overhead, Uncertainty, and Interference in Wireless Networks*, Ph.D. Dissertation, University of Delaware, 2014.

  – In general, the performance of many wireless systems is approaching the fundamental limits on transmission capacity. For example, current commercial wireless standards such as 3GPP LTE-A and IEEE 802.11ac have a near-optimal physical layer. In order to meet the ever growing demand for capacity, other directions for improving network performance must be found.

  In most existing research on wireless networks, overhead, the "non-data" portion including coordination, control signaling and other costs of serving different purposes, is assumed to be negligible. However, the final application throughput could be much lower than the theoretical bounds as a result of overhead, especially in large and dynamic networks. Therefore, it is critical to quantitatively analyze the overhead in wireless networks, which could provide clear insights on the performance in practical systems and could help to identify opportunities for improvements in their designs. Surprisingly, the fundamental limits on overhead are largely unknown, and the framework needed to design overhead-aware systems has not been adequately investigated.

  In addition, interference is one of the main performance-limiting factors in most future wireless applications. Conventional "interference avoidance" techniques might not be feasible because the degrees of freedom (for example, bandwidth, number of orthogonal codes, and time) might be limited. Although the interference can be mitigated quite efficiently with centralized control, existing approaches are usually very sensitive to channel uncertainties; if the knowledge of the channel state information is imperfect, the system performance could be severely degraded. Also, collecting accurate information incurs a significant amount of overhead due to the time-varying nature of the wireless medium. Thus, it is imperative to jointly consider overhead, uncertainty, and interference.

  In this dissertation, we investigate practical and overhead-aware designs that can achieve better performance in a realistic networking context. We start with a simple, single-user, two-hop cooperative relaying network model. For this model, we first prove that M-group cooperation is the optimal distributed space-time block coding strategy when neither central control nor inter-relay communications is permitted. Then, we consider the relay selection problem where a small and acceptable amount of overhead is allowed. The tradeoff between the feedback overhead and the performance is investigated via rate distortion theory. Compared to existing research, which is usually highly dependent on the specific implementation approaches, the analysis presented here addresses the fundamental tradeoff of a general network. Using our theoretical results, we also compare practical centralized and decentralized relay selection schemes in terms of spectral efficiency.

  Then, interference-limited networks with multiple concurrent transmissions are studied. We analyze and compare the performance of cooperative and non-cooperative schemes. Although cooperation among relay nodes increases the reliability of point-to-point transmission, it also produces a higher level of interference and degrades the overall performance of a multi-user network. The tradeoff between cooperative gain and the additional interference is investigated, and a criterion which determines whether we should cooperative or not is derived.

  We next focus on multi-hop linear networks, which have one or more intermediate nodes along the path that receive and forward information via wireless links. Instead of assuming equal hop distances, we propose a novel model that permits randomness in the node locations, and then we determine the optimum number of hops for maximizing the end-to-end spectral efficiency. Then, for a multi-hop linear network with cooperative relays, a relay deployment strategy is proposed and studied.

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After that, for downlink multi-user networks, we present a novel quantization technique, sparse coding quantization (SCQ), which is an extension of classic vector quantization (VQ) and provides a balance between performance and complexity. In particular, the computational complexity of conventional VQ can be significantly reduced by applying SCQ, with a negligible reduction in performance. Comparisons among different quantization techniques are also provided. Beside considering specific quantization schemes, we also study the overhead-performance tradeoff for general MU-MIMO systems by applying a rate distortion framework.

Finally, we investigate robust a user pairing problem for a heterogeneous network in the presence of channel uncertainty. Different definitions of robustness and uncertainty are considered to formulate the corresponding optimization problems. We develop an algorithm that is robust to uncertainty in channel measurement and thereby performs well in practical systems. Simulation results validate the robustness of the proposed method.

- Yao Xiao, *Cross-Layer Design for Wireless Cooperative Networks*, Ph.D. Dissertation, University of Delaware, 2014.

  - Cooperative communications has been shown to be effective in combating fading in wireless channels. In order to realize the potential benefits promised by cooperative communications in practical wireless networks, careful cross-layer design is essential. In particular, investigations of the interactions among the physical, link, and network layers are critical in developing cooperation-enabled MAC or routing protocols. Recently, cross-layer design for cooperative networks has become a very active research area; many efficient and elegant cooperative networking techniques that provide significant performance gains have been proposed.

    Cooperation, however, also introduces new challenges, including increased overhead and interference, that must be addressed in order to efficiently implement cooperative networks. Although cooperation is promising in improving performance, it requires much more overhead to implement compared with conventional point-to-point communications. In addition, with cooperation, the interference environment will change; this means that new interference management techniques are required.

    In this dissertation, we focus on the overhead-performance trade-off and interference management for wireless cooperative networks. The overhead in implementing cooperation, particularly the overhead to estimate the channels, select the relay(s), and coordinate the transmissions, is investigated. Taking into account the overhead, the spectral and energy efficiencies of several different relaying schemes are studied. Through analyses and simulations, we demonstrate the impact of the overhead on these efficiencies, and provide guidelines for determining the appropriate cooperative scheme for specific applications.

    In order to realize the promised benefits of cooperative communications in practical wireless networks, cooperation-enabled routing algorithms are essential. Motivated by the analysis of the performance-overhead trade-off for cooperative relaying, we propose a novel cooperative routing algorithm that reduces the amount of overhead incurred in implementations and hence provides a significant performance gain. Specifically, we describe Location-Aware Cooperative Routing (LACR), a routing protocol for multi-hop wireless networks, which incorporates cooperative transmissions into geographical routing. Simulation results show that LACR performs well, providing a high probability of discovering a route with low overhead; these advantages are particularly apparent when the network is sparse.

    In addition to requiring more overhead, employing cooperation in wireless networks affects the performance of existing interference management techniques. Focusing on multi-hop linear cooperative networks, we investigate the impact of cooperation on spatial reuse scheduling. The impact of enabling spatial reuse and incorporating cooperation on the network throughput is studied. Through analyses and simulations, we show that appropriate reuse is critical for efficient networks, and incorporating cooperation is effective in improving the network performance when the direct links are suffering high outages. Furthermore, the reuse factor that maximizes the network throughput is derived, the performance of which is illustrated via simulations.

6 Conclusions & Future Directions

This project demonstrated the importance of determining better methods of encoding control and measurement information to the improvement of wireless communications networks. It was shown that the rate distortion function and multi terminal information theory lies at the heart of the optimal designs of such encodings. A key consideration is that these encodings should be optimized not only with respect to a single communications link, but with respect to a function which a central resource controller will be calculating over many links. Fundamental limits for overhead performance tradeoffs for several simple network control models were calculated using a novel adaptation of the Blahut Arimoto algorithm, and practical quantization schemes were devised that approached these limits. It was demonstrated that interaction can yield substantial reductions in the required amount of overhead, but comes at the cost of substantial delay, and hence a tradeoff between overhead rate, performance, and delay must be considered. Extensions of the ideas to more complex models in cooperative communications, and into the realm of rateless joint source channel codes were considered.

The project leaves many important avenues for future research. The first would consider interaction models which enable the feedback quantizers to be heterogeneous across users. Substantial further rate gains are expected with this larger dynamic program, at the cost of a large amount of extra complexity. Careful research must be done to devise suboptimal, but simple, heterogenous interactive schemes which can approach the associated optimal dynamic programs. Additionally, recent research regarding the fundamental limits for interactive function computation should be harness to compute overhead performance tradeoffs in these scenarios.

Another important direction for future research is the consideration of the interplay between the quantization of queueing state in multi-user MIMO communications and the quantization of lower layer channel state. Both fundamental limits and practical schemes are of interest in this regard. Additionally of interest would be further modeling from measurement data of the overhead performance tradeoff experienced by practical controllers in commercial wireless networks. A final direction for future research is the incorporation of resource control function computation models into rateless joint source channel coding systems.

1.

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Abstract

The overarching goal of this project was to characterize the tradeoff between overhead and performance for resource allocation, link adaptation, and control in distributed wireless networks. Different practical resource control, link adaptation, and scheduling algorithms, ranging from completely academic to those already specified in standards, were considered through the lens of the overhead they require to meet a given performance. The project considered performance primarily from physical layer centric metrics such as sum rate and throughput.

The key novel idea guiding the research was that wireless network and resource control algorithms, which must all make decisions dependent on network state that is distributed throughout the network and not available at any one location, could be viewed as distributed lossy source codes designed for computing control functions. Distributed lossy source coding and distributed and interactive function computation theory can then characterize the tradeoff between overhead and performance through a rate distortion function, where the rate reflects the amount of overhead, and the distortion reflects the gap between the performance of the decisions made and those an omniscient controller would make.

To make a case to the community for the need for the research, the project began with a thorough analysis

of the overhead required for the resource measurement and control signaling in the 3GPP LTE and LTE advanced standards. A tutorial on this topic was written, which elucidated that the present wireless standards waste nearly a quarter to a third of downlink transmission on poorly encoded non-information bearing resource measurement and control signals [29,33]. This enabled the investigators to make a strong case for studying the optimal encoding of control signals for wireless resource allocation. Previous studies along these lines have focused on adaptation of a single link, with extensive prior research studying rate distortion functions and compressors being designed for precoding matrices for MIMO communications. However, very little work has considered the design of compressors angled at computing a function that depends on the channel state of multiple users simultaneously, and it was precisely this subject that the project set out to investigate.

Next, we set out on analyzing the fundamental limit for the overhead performance tradeoff for a family of simple scheduling algorithms [19,21,33,34,35]. Three different, but closely related, schedulers reflecting three different collections of physical layer capabilities were selected. The first scheduler, motivated by an adaptive modulation and coding based physical layer, aimed to both select a user with the highest channel quality to schedule, as well as learn this users channel quality, thus computing both an arg-max and a max across users. The second scheduler, motivated by a physical layer utilizing a sophisticated hybrid-ARQ or rateless coding scheme, aimed only to learn the identity of a user with the highest channel quality, thus computing only an arg-max. The third scheduler was based on an any-cast oriented physical layer desiring to communicate a common message to any user with the highest channel quality, and thus computing only a max.

Using multiterminal information theory, the minimum amount of information to compute these three schedulers with a given performance/spectral efficiency accuracy, was determined as an instance of a rate distortion function [33,35]. It was shown that, although some small rate savings relative to blindly forwarding channel state are possible when computing the functions losslessly in a non-interactive manner, substantial rate savings scaling favorably in the number of users can be obtained if either interaction between the controller and users is allowed, or some loss can be tolerated by the scheduling algorithm, or both. In order to compute the associated rate distortion tradeoffs, a new variant of the Blahut Arimoto algorithm was designed for lossy distributed function computation [28]. Additionally, practical source compressors and quantizers were designed which approached the rate distortion limits for both non-interactive and interactive cases of the three simple scheduling models above [19,33,34,35] as well as for more complicated link adaptation models from multiple user MIMO communications [14,17,32].

Another important direction of research undertaken in the project was toward overhead and performance considerations in cooperative communications and relaying [2,3,4,7,8]. Here new protocols were devised addressing similar non-idealities such as imperfect channel estimation, while simultaneously reducing the amount of overhead required through the use of mechanisms such as channel dependent timers [2,4,13,31].

Also, motivated by the need not-only to compute control decisions at a controller in a manner requiring minimal information exchange with users in the network, but also to convey the salient part of the control decisions back to the users over their unreliable channels, the project exerted substantial effort on the joint source channel coding problem for unknown channels. Here, we have studied novel rateless coding schemes for high throughput transmission for a wide range of single and multi-terminal sources and different channel environments [6,9,10,20,23,24,26,27,30]. Different from existing rateless systems, we have focused on the application of hybrid analog-digital joint source-channel coding schemes, inspired in novel developments in the field of analog joint source-channel coding.

The hybrid schemes we have developed consist of two sub-blocks concatenated in parallel: on the one hand, a digital channel encoder, which produces coded bits from the input bits, as in standard rateless systems. On other hand, a digital-to-analog encoder, which produces real numbers (or multiple discrete points) from the input bits. The idea of this research is to take advantage of the analog component of the

hybrid scheme to obtain high throughput communications, and more robustness against changes in the channel conditions, something that would be difficult to achieve if only standard digital channel codes were utilized. On the other hand, the use of pure digital-to-analog encoders would lead to significant error floors, with the consequent performance degradation. Thanks to the use of the digital channel code sub-block, these error floors can be substantially reduced to achieve excellent performance.

In summary, the research on the project thoroughly demonstrated the importance of the focus on the design of encodings of control signals in wireless systems, and that these designs can be guided by fundamental limits set out by multiterminal source coding theory and recipes from practical quantizers for function computation.

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37.) Y. Xiao, H. Feng, and L. Cimini, "Optimal Spatial Reuse in Multi-Hop Wireless Cooperative Networks," IEEE Trans. Wireless Commun., submitted.

Changes in research objectives (if any):

None

Change in AFOSR Program Manager, if any:

Dr. Robert Bonneau was program manager of the complex networks program until he left to join a new job.

Extensions granted or milestones slipped, if any:

None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

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